ORIGIN OF THE NEW SOUTH WALES TORBANITES.

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(Plate i; three Text-figures.)

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Contents.

Introduction.

Problems of the origin of torbanite extend into three main fields of investigation, namely, the biological origin of the organic matter, the environment in which it was deposited, and the metamorphic evolution of the torbanite deposits. Recent palaeobotanical research has contributed valuable knowledge concerning the organism responsible for the original organic matter; but other biological aspects of the origin of torbanite, together with geological problems of environment of deposition and metamorphic evolution, have received but little attention. The purpose of this paper is to present biological evidence of the algal origin of the organic matter, and to put forward the results of an investigation into the environment of deposition and metamorphic evolution, with the object of developing a complete history of the origin of the torbanite deposits. The problems of origin are numerous, and frequently obscure, but it is hoped that the results recorded here may form, at least, a working hypothesis for future research.

ORIGIN OF ORGANIC MATTER IN TORBANITE.

Previous Literature and Opinions.

Early attempts to explain the nature and origin of the organic matter occurring as a translucent, yellow substance (gelosite and retinosite) in the form of minute disc-shaped bodies, were based on the assumption that oily hydrocarbons were present in the torbanite. Strzelecki (1845) referred to it as pure bitumen; Quekett (1853) believed it was formed by the impregnation of clay with some kind of liquid hydrocarbon; Traill (1853) described it as consisting of much bitumen mingled with clay.

The first suggestion that torbanite may have been formed from plant debris was made by Redfern (1855), who advanced the theory that the organic bodies were macerated vegetable cells—possibly spores or pollen. Clark (1866) first described the Australian torbanite as containing a high percentage of mineral oil, probably contained in cells. Later he suggested that it was formd by specialized decomposition of resinous wood which, under other conditions, would have become coal. Skey (1874) believed it originated from the absorption of petroleum by clay, followed by the interaction of hydrocarbon acids with silicates of alumina, which gave a solid substance, torbanite. Dixon (see Carne, 1903) pointed out the impossibility, in the case of richest torbanites, of saturating less than 6% of mineral matter with over 90% of hydrocarbons. Wilkinson (1880) believed that the organic bodies in Australian torbanite were lycopodian spores.

An important development in research on the origin of torbanite took place towards the close of the nineteenth century, when David (1889) first suggested the possibility of an algal origin. He published a paper discussing the means by which spore material could have accumulated in sufficient quantities to form torbanite, but added an appendix describing structures which, he considered, bore a resemblance to algae of the Volvocineae; he suggested that the organic matter might have been formed from an alga. Soon after David's suggestion, the subject was taken up by two French scientists, Bertrand (C. E.) and Renault, who developed the algal theory and published a number of papers (1892 to 1901) describing the algae in torbanites from different parts of the world. They observed, in French and Scottish torbanites, masses of thick-walled cells, closely packed and radially arranged in the algal colonies, while in Australian torbanites they described an envelope, built up of a single layer of cells enclosing a large, central cavity. This difference in morphology was believed to be due to different genera of algae, and the generic names *Pila* and *Reinschia* were given to the two forms, respectively.

Seward (1898) supported the algal theory; but the results of Bertrand and Renault were not generally accepted—their evidence lacking conviction with regard to cell structure and means by which the algae could be preserved to form torbanite. Many workers still believed that the organic bodies were spores of vascular plants. Jeffery elaborated the spore theory in a number of papers (1909–1924), dealing mainly with the Kentucky torbanite, in which the algal cell structure is poorly shown; but he claimed that the spore theory applied to all torbanites. He described the compact bodies in the French and Scottish torbanites as microspores, and the large bodies possessing central cavities—typical of Australian types—as macrospores. The fuzzy, indefinite margins and spongy appearance, exhibited by the bodies in thin sections, were, he explained, oblique sections of rough spore coats.

Conacher (1917) believed that the organic bodies were particles of resin; the internal cell structures were conchoidal cracks formed by shrinkage; and the cavities were gas bubbles. He first observed certain cone-in-cone structures within the bodies and a pit on the surface at the base of each series of cones. These were eventually shown by Temperley (1936) to be important features in the structure of the algal colony, but Conacher attributed them to symmetrical shrinkage cracks. Cunningham-Craig (1916, 1919) attempted to revive old theories, involving the consolidation of liquid hydrocarbons, by suggesting that the organic bodies were inspissated petroleum residues. His views were not accepted by other investigators.

Zalessky (1914 to 1926) studied the Russian torbanites, and recorded evidence in support of the algal theory. Apparently he was the first to recognize the similarity between the fossil alga of torbanite and the living type *Botryococcus Braunii*. He described algal deposits on the shores of Lake Balkhash, closely resembling coorongite from South Australia, and attributed both to *Botryococcus*. He suggested that similar material might have been the original organic matter of torbanite, but still held to the belief that the algal deposits had been impregnated with liquid hydrocarbons. Zalessky also described algae in several of the Russian torbanites, emphasizing certain resemblances to living forms.

The next valuable contribution to the algal theory was made by Thiessen (1925), when he published his views concerning the relations between coorongite and torbanite. He amplified Zalessky's observations on the similarity between the fossil alga and *Botryococcus*, and described the peculiar composition and decay-resisting properties of coorongite. He explained that the cell walls of the alga were responsible for the particular nature of both coorongite and torbanite, and showed that the latter could be derived from algae, without the addition of any extraneous hydrocarbons. In later work, Thiessen used the algal theory as a basis for differentiating between torbanite and other coals.

White (1926, 1930) accepted the views of Thiessen, and described algal sapropel as the peat-stage of torbanite. The earlier work of Bertrand (C. E.) and Renault was followed up by Bertrand (P.) (1927, 1930), who accepted the similarity between *Pila* and the Botryococcaceae, but still maintained that *Reinschia* belonged to the Volvocaceae. He also described the grouping of cells in the fossil colonies—a feature treated in greater detail by Temperley in more recent work.

The algal theory was more or less generally accepted by 1930; but some doubt was still expressed, as evidence had not been established to prove, beyond all doubt, that the structures in the organic bodies were algal. This was due to the fact that the detailed morphology of the fossil alga and the living form, which it closely resembles, had not been fully and systematically worked out. This remained to be accomplished by Blackburn and Temperley. The living alga, *Botryococcus Braunii*, was studied and described by Blackburn (1936); and the structures in the organic bodies of torbanite were described by Temperley (1936), and explained by comparison with those of the living alga. The results of this work provide convincing evidence that the organic bodies in torbanite are fossil colonies of an alga closely related to the living type, *Botryococcus Braunii*. Their conclusions, regarding the similarity between the two, are based on the following common characteristics:

1. Each consists of a framework showing, in its structure, evidence that it was built up from the secretions of a colony of cells.
2. Each has a cone-in-cone or dome-in-dome structure, which could only be built up by each new cell secreting a complete new cup after each process of cell division, and by each old cell remaining in the structure of the colony—there playing the part of binding the cells together.
3. Each has a globular form when small.
4. Each shows a certain degree of polymorphism when large. This polymorphism, in each case, involves an alternative form, in which the cells are more closely packed and no longer arranged in groups, while, at the same time, the amount of secreted matter at the centre of the colony is very small.
5. Each consists of secreted material with properties which include high resistance to decay, and yield a paraffin on distillation.

General Morphology of the Living Alga, Botryococcus Braunii.

It is not intended that this section of the work should make any biological contribution to the nature of the alga found in torbanite. The main object is to show that the New South Wales torbanites are composed of the fossil remains of an alga closely related to *Botryococcus Braunii*, and to explain the structures of the organic bodies in terms of the morphology of this alga. The following, brief description of *Botryococcus*, based on the work of Temperley and Blackburn, is included as a necessary preliminary to the interpretation of the structures which can be recognized in the organic bodies of all the torbanites of the New South Wales deposits.

The alga consists of a single, pear-shaped cell enclosed within a cellulose wall, and covered, at the large end, by a cap of cellulosic and pectic substances. The cell wall is surrounded by a cuticular thimble possessing a small opening which allows the cap at the large end of the cell to communicate with the exterior. Excess fatty substances, secreted by the cell, form a thick cup-like structure round the thimble (Fig. 1A). The cup and thimble consist of firm substances possessing a large degree of elasticity. The cell reproduces by longitudinal division, and each daughter-cell secretes a new cup within the original thimble and cup, which become extended to accommodate the new cell (Fig. 1B). The daughter-cells protrude slightly from the old cup, which binds them together, and they divide in a manner similar to the original cell, producing four cells, complete with thimbles and caps, and arranged in two pairs within the original cup (Fig. 1C). Cell division continues building up a globular colony; the old, fatty cups fuse to form the matrix of the colony; and the old, cuticular thimbles form a kind of supporting skeleton. A layer of pectic mucilage, derived from the cell caps, forms around the colony, and when 40 to 60 cells are formed, the colony either branches or breaks down to form several colonies loosely connected by threads. A large mass of cells is formed in this way, representing a compound colony, which is the algal body seen in thin sections of torbanite.

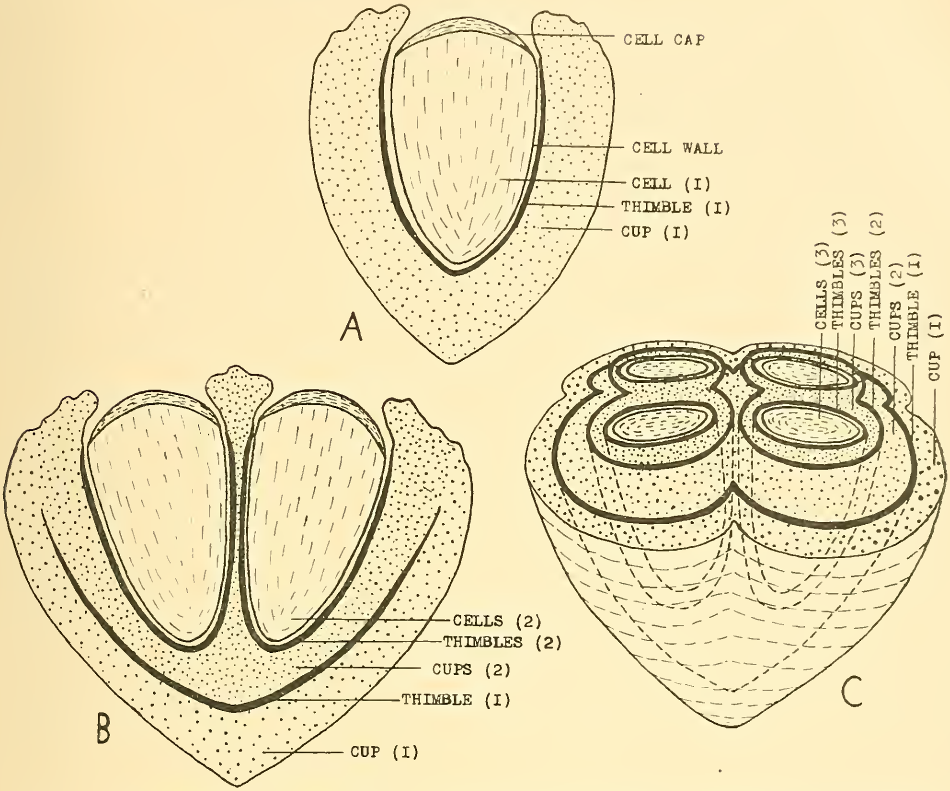

Fig. 1.—Diagrammatic illustration of reproduction and colonial structures in *Botryococcus Braunii*. (After Blackburn.) (× 2,000.) A, Single cell; B, After division to form two cells; C, After division to form four cells.

Structural modification in the compound colonies gives rise to the different forms of algal bodies originally described as *Pila* and *Reinschia*. This is determined by the way in which development occurs after the simple colony has reached its maximum size. Branching in all directions and the fusing of old cups cementing the branches together produces a solid botryoidal mass. This is the compact form of compound colony found in the Scottish and Autun torbanites and referred to as *Pila*. Development of the simple, globular colony may proceed in such a way that new groups of cells are closely packed round a central cavity. This type of compound colony, when flattened by compression, gives rise to the disc-shaped, algal body containing a collapsed central cavity, which is typical of Australian torbanites, and which is referred to as *Reinschia*.

Interpretation of the Structures in the Organic Bodies of Torbanite.

The micro-constitution of torbanite has been described in a previous paper (Dulhunty, 1939*a*), and it has been emphasized that all the New South Wales torbanites exhibit a typical micro-structure in thin sections. This consists of yellow, translucent, disc-shaped, organic bodies lying parallel to the bedding planes, and separated by thin films of opaque, inorganic matrix which forms a kind of skeleton. In some high-grade torbanites the organic bodies are packed so closely that the matrix occurs only as isolated fragments. The organic bodies consist of gelosite and retinosite, and their internal structures may be correlated with the morphology of *Botryococcus Braunii* in the following manner:

In the living colonies, the cups, secreted by the cells, form the matrix; and the thimbles, marking the positions of the old cells, form a supporting skeleton. When the colonies die, the cups and thimbles form a tough, rubbery mass, resistant to decay and remaining long after the death and disintegration of the algal cells. This material is preserved to form the algal bodies of torbanite; and the internal structures are the thimbles or skeletons of the original colonies. The thimbles give a true picture of the structure of the colonies, each cell having possessed a thimble, held in position by matrix formed from the old cups. In vertical sections, the bodies exhibit a central, longitudinal dark band of variable width (Plate i, A), representing the collapsed central cavity of colonies which belong to the hollow, spherical (or *Reinschia*) form. The apparent absence of a central cavity, seen in some sections, may mean that the colony belongs to the compact *Pila* form, but, in most cases, it is due to the section passing through the margin of the colony. The central cavities are rarely seen in horizontal sections which are parallel to the plane occupied by the flattened cavities. The bodies frequently show a series of bulges, arranged more or less regularly round their margins (Plate i, B), giving rise, in some cases, to a botryoidal appearance. The bulges represent simple colonies, fused together to form compound colonies.

The arrangement of cells and other detailed structures, within the algal bodies, are revealed by high magnification (250–500 diameters), and commonly consist of rectangular lines, oval shapes, funnel-shaped structures, cones and radiating or branching lines—depending on the position and direction of the section. The rectangular system of lines, usually seen in a horizontal section above or below the central cavity, is produced by closely packed cells having divided and redivided in two directions at right angles—each producing four daughter-cells. These are situated within the original mother-cell cups, which have been extended and compelled to assume a rectangular shape, owing to the proximity of neighbouring cups (Fig. 2B). The oval shapes (Plate i, C) appear in both vertical and horizontal sections which pass obliquely through a series of cells (Section m–n, Fig. 2A), in which the new cups are complete and well preserved. Cone-sections or funnel-shaped structures are particularly common (Plate i, D), arising from sections in the direction o–p (Fig. 2A). They represent longitudinal sections of the cell thimbles (Fig. 2C) and may appear in vertical sections

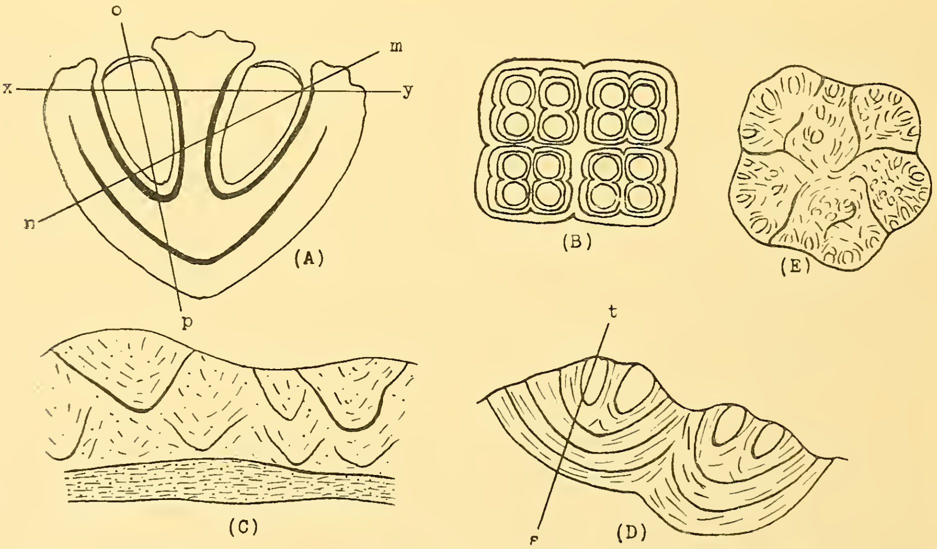

Fig. 2.—Diagrammatic illustration of algal structures in gelosite and retinosite. A, A pair of cells with cups and thimbles (× 1,200); B, Cells in groups of four, giving rise to rectangular arrangement seen in horizontal sections (× 420); C, Portion of compound colony showing funnel-shaped structures representing old thimbles (× 580); D, Portion of compound colony, illustrating the way in which cone-in-cone structures arise in sections along s-t (× 420); E, Compound colony showing branching lines which represent margins of simple colonies (× 100).

with slightly flattened or rounded apices, directed towards the collapsed central cavity. In horizontal sections, they are usually seen at the margins of the colonies. Smaller cones may occur within larger ones, producing a cone-in-cone structure. This is seen in sections passing through the side of a colony, built up by the development of new cups within the mother-cell cups that have become extended but still retain their identity (Section t–s, Fig. 2D). Radiating and branching lines (Plate i, E), forming large structures, are usually present in both vertical and horizontal sections of compound colonies. These lines are heavier and more definite than the fine lines formed by sections through cell cups and thimbles, and represent the margins of the simple colonies in the compound colonies (Fig. 2E).

Distinction between Spores and Algal Bodies.

The general appearance of algal colonies may be compared with the macrospores shown in Plate i, F and G. It will be noted that the spores possess sharp-cut, well-defined margins; and the internal structures, when present, consist of typical markings, shown by distinct lines. The algal colonies possess indefinite "fuzzy" margins, frequently appearing pitted; and the internal structures consist of minute cell cavities, in compact masses regularly arranged in groups or radiating cones. Spores are preserved in clear, structureless substance, while the material of algal colonies is less transparent, being flecked with tiny inclusions of club-like bodies and opaque specks; and variations in refractive index give an uneven distribution of transmitted light. Characteristics, typical of macrospores and normal algal colonies, serve to distinguish between microspores and very small, algal colonies. Both spores and algal colonies are anisotropic in thin sections; but all the algal colonies, in any one section, are optically continuous, with respect to the polarization laminae (Dulhunty, 1939*a*), extending across the full width of the section.

Coorongite and its Relations to Torbanite.

The recent algal deposits of coorongite, forming from time to time in the vicinity of the Coorong, South Australia, have attracted much attention, owing to the peculiar nature of the substance, and the question of its origin.

It was originally believed to be the remains of some cryptogamic plants; but Thiselton Dyer (1872) showed that its composition resembles that of a hydrocarbon rather than a carbohydrate, and suggested that it might be the secretion of a plant, or the product of an oil spring. David (1889) recognized the similarity, with regard to certain properties, between coorongite and torbanite. Cumming (1903) also demonstrated the hydrocarbon nature of coorongite. Zalessky (1914) studied organic deposits closely resembling coorongite in the Ala-Kool of Lake Balkhash (see p. 27), and suggested genetic relations between this material and torbanite.

Coorongite was observed forming on the surface of shallow lakes near the Coorong in 1919 (Mawson, 1938), when it became evident that it was formed by microscopic pond-life. The true algal nature of coorongite was clearly demonstrated by Thiessen (1925), but he suggested that it was a type of alga previously unknown. The more recent work of Blackburn (1936) and Temperley (1936) has placed, beyond all doubt, the fact that the alga, responsible for the formation of coorongite, is *Botryococcus Braunii*. This is now generally accepted (Chapman, 1941).

Coorongite collected from the Coorong region, together with specimens supplied by Sir Douglas Mawson, have beeen examined by the author. It possesses an extraordinary degree of toughness and elasticity, giving the well-known rubber-like properties. Flat pieces, half an inch to an inch in thickness, can be folded in two without breaking, after which they will return to their original shape. It is sufficiently soft to be cut with a knife-blade, but firm enough to be scratched with a sharp point, which produces a light-yellowish streak. When broken or torn, the fracture surface is dark greenish-brown in colour and exhibits a bright, resinous lustre.

New coorongite is translucent to bright light in sections up to half an inch in thickness. Its substance is compact and homogeneous, with the exception of sand-grains and vascular-plant material, accidentally introduced. The specific gravity is slightly greater than 1·0. It ignites readily in the flame of a match, and burns with a bright, smokeless flame, which is almost odourless.

The microscopic structures of coorongite have been described in detail by the investigators who have established its origin. Thin sections of coorongite can be prepared for microscopic examination by means of a microtome, or merely by cutting thin shavings with a razor and staining with alcoholic safranin. All sections show some trace of the algal structures already described in connection with the interpretation of the structures in torbanite. Some specimens exhibit well-preserved colonies, with typical grouping of thimbles (due to regular cell division) and stalk-like features, formed by the fusion of the basal portion of older cups. Other specimens show very little structure at all, owing to almost complete fusion of the algal debris to form an apparently structureless mass.

The principal evidence confirming the fact that coorongite represents the algal "peat-stage" of torbanite may be summarized as follows:

1. Both substances are composed of the remains of a unicellular colonial alga.

2. In the case of coorongite, the alga is the living form *Botryococcus Braunii.* In the case of torbanite, it is an alga so closely related to *Botryococcus Braunii* that botanical authorities consider the creation of a new genus unjustified.

3. Coorongite possesses toughness and elasticity unique among recent organic deposits; torbanite possesses elasticity and resilience unequalled by any other carbonaceous sediment.

4. Coorongite consists essentially of hydrocarbons, as compared with the carbohydrates of vascular-plant debris. Torbanite, when heated, produces paraffin oils, as would be expected from the thermal decomposition of polymerized, fatty hydrocarbons. Coal, derived from vascular-plant debris, produces an aromatic tar, when heated, as would be expected from the thermal decomposition of bituminized carbohydrates.

5. Both coorongite and torbanite are similar with respect to colour of streak, lustre, fracture, specific gravity, general colour, high volatile/fixed carbon ratio (proximate analysis), high hydrogen content (ultimate analysis), and oxidation products when heated with nitric acid.

6. If the oil yield from thermal decomposition is expressed as a percentage by weight of the volatile content, the figure for torbanite varies between 60 and 90%; coorongite between 65 and 75%; coals and cannel coals between 15 and 40%.

7. Both coorongite and torbanite emit a strong, light yellowish-white fluorescence in ultra-violet radiation, while ordinary peats, coals and cannel coals, derived from vascular-plant debris, do not fluoresce at all.

8. Sections of coorongite and torbanite transmit amounts of infra-red radiation much larger than ordinary coals, cannel and oil-shales.

9. Coorongite possesses unusual properties of resistance to decay and atmospheric oxidation, which would enable it to be preserved and fossilized under ordinary conditions of burial in coal-measures.

There seems to be no doubt that torbanite is derived from an algal sapropel which was the chemical, physical and biological equivalent of coorongite. That organic evolution should have allowed the organism to remain almost unchanged over the immense length of time which has elapsed since the Permian coal-measures were laid down is extraordinary, but similar stability of form appears to have existed during the descent of other primitive organisms, such as the brachiopod, *Lingula*; although, in some cases, new and more complex forms may have been derived by evolutionary branching from the stable lines of descent. The very primitive nature of the living *Botryococcus* suggests that the organism has not changed for a very long time, and justifies the belief that it has descended from the late Palaeozoic alga preserved in torbanite, without appreciable modification.

ENVIRONMENT OF DEPOSITION.

The environment of deposition may be regarded as a broad heading which covers the major geological problems relating to the origin of torbanite. It includes the study of conditions under which the organic matter accumulated, as well as those effecting its preliminary preservation. The conditions of accumulation have been studied, firstly, with respect to the regional environments of sedimentation producing the coal-measures in which the torbanite deposits occur, and secondly, in relation to the conditions prevailing in the localities where the algal deposits were formed. Finally, consideration has been given to the environment of preservation enabling the algal remains to be preserved prior to, and immediately after, burial.

Palaeogeographical Considerations.

The occurrence and general distribution of torbanite in New South Wales have been described (Carne, 1903; Dulhunty, 1942*a*). Deposits occur in both the Upper and Lower (or Greta) Coal Measures of the Kamilaroi System. These two divisions of coal-measures represent distinct phases of sedimentation, being separated by thick beds of marine strata. In considering the palaeogeographical relations between coal-measure sedimentation and the formation of torbanite, the Upper Coal Measures will be dealt with first, as they are the most important torbanite-bearing strata, and provide more evidence relevant to the problems of origin.

The area originally occupied by Upper Coal Measure sediments is indicated in Fig. 3, which has been reproduced from a previous paper (Dulhunty, 1942*a*). The measures were deposited in what may be described as the original "Kamilaroi Basin"; but the use of this term, in referring to the whole area in which coal-measures occur, is somewhat confusing and perhaps unwise, as later earth movements warped the Kamilaroi sediments into three separate, structural areas: the coastal area from Newcastle in the north to Nowra in the south, extending westward to Lithgow, Rylstone

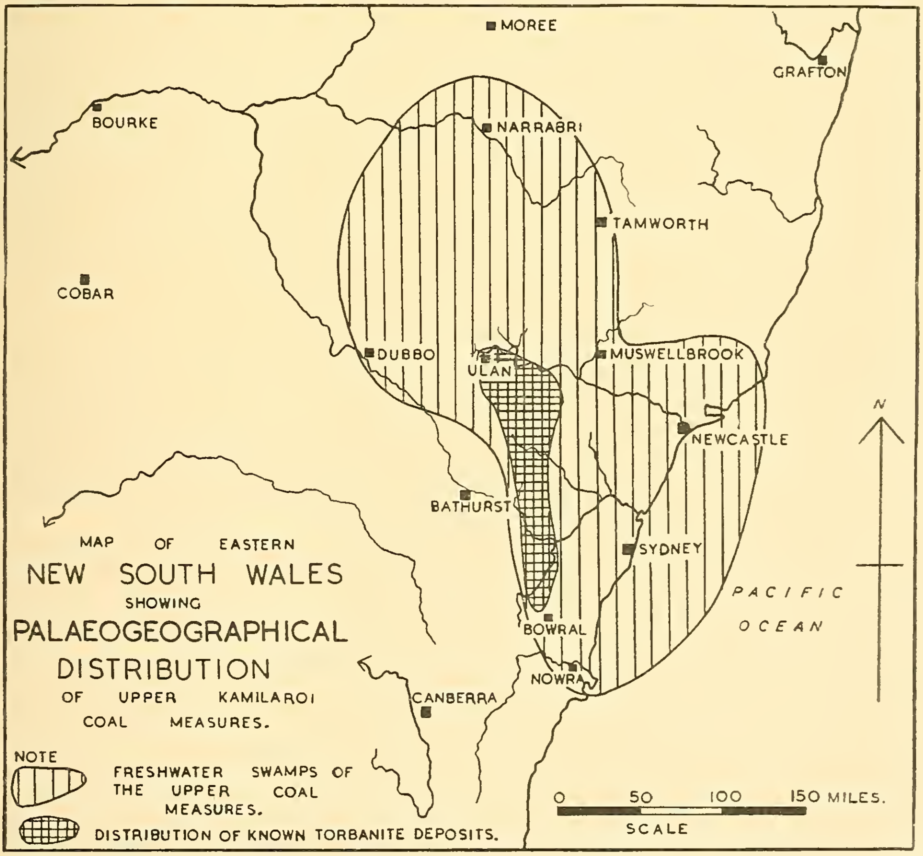

Fig. 3.—Map showing the relation between the distribution of known torbanite deposits and the probable area covered by the freshwater swamps of the Upper Coal Measures.

and Muswellbrook (Raggatt, 1938); the Oxley Basin (Dulhunty, 1940), situated between Muswellbrook, Coolah and Gunnedah; and the south-eastern margin of the Great Artesian Basin between Gunnedah, Dubbo and Narrabri (Kenny, 1928, 1929; Lloyd, 1935; Dulhunty, 1939*b*). It is intended, for the purpose of the present paper, to refer to the coastal area, extending inland to Lithgow and Rylstone, as the *South-Eastern Region* of the Kamilaroi deposition, and those portions now within the Oxley and Great Artesian Basins between Muswellbrook, Dubbo and Narrabri, as the *North-Western Region*.

The most important deposition of coal-measures took place in the South-Eastern Region, which included the original centre of Kamilaroi deposition. The central portion of this region is covered by Triassic sediments; but outcrops occur in the southern, south-western, western and northern sides, in areas known as the Southern, South Western, Western and Northern Coalfields, respectively. Outcrops, occurring on the southern side of the Oxley Basin along the Goulburn River between Ulan, Rylstone and Baerami (Dulhunty, 1941), will be considered a part of the Western Coalfield in the following discussion.

Distribution of Torbanite in the Upper Coal Measures.—Although the Upper Coal Measures extend over the wide region indicated above, the formation of torbanite was confined to a comparatively small, elongated area, trending roughly north-west and south-east along the western side of the South-Eastern Region, within the Western and South-Western Coalfields as illustrated in Fig. 3. Detailed evidence of this distribution has been discussed by the writer (Dulhunty, 1942*a*).

The Upper Coal Measures are comparatively thin (less than 600 feet) along the western and south-western margins of the South-Eastern Region; but they attain great thicknesses amounting to over 3,000 feet in the central portions, where there are upper and lower sections known as the Newcastle and Tomago Stages, respectively. In the Western and South-Western Coalfields, where torbanite deposits occur, the upper or Newcastle Stage alone is represented, having overlapped the Tomago Stage (Dulhunty, 1941; Raggatt, 1938). No deposits have been found in the Tomago Stage, although it outcrops extensively in the Hunter Valley. It follows that the torbanite-formation in the Upper Coal Measures was confined not only to the western side of the South-Eastern Region, but also to the Newcastle Stage. The stratigraphical distribution of deposits within the Newcastle Stage has been described and illustrated (Dulhunty, 1942*a*), showing that the majority of the deposits occur in the lower portions, while in the topmost portion, above the No. 2 Coal Seam, there is none. A definite tendency persists for torbanite to occur on, or near, coal-bearing horizons.

The grouping of the torbanite deposits on the western side of the South-Eastern Region, their confinement to the Newcastle Stage of the Upper Coal Measures, and their limitation to certain zones within this stage, call for an explanation which must be sought in terms of regional environment and changing conditions of sedimentation.

Regional Conditions of Upper Coal Measure Deposition.—The palaeogeography of the Upper Coal Measures has been dealt with by several writers, including Walkom (1913), David (1932) and Raggatt (1938). The main events, important in relation to the origin of torbanite, may be summarized as follows:

The coal-measures of the Tomago Stage were built up by sediments derived from lands of low relief, under conditions of general quiescence. The change from these conditions to those which produced the sediments of the Newcastle Stage was accompanied by important earth movements. There was extensive elevation of country surrounding the basin, and high lands resulted, particularly to the north-east. A great land mass, described by Sussmilch and David (1919) and David (1932) as Tasmantis, existed to the east of the present coastline, forming an effective barrier to the sea. Continued sinking of the basin, particularly in the northern and central portions, gave rise to widespread deposition of freshwater sediments (the Newcastle Stage), which covered the entire area previously occupied by the Upper Marine sea. Coal-forming conditions of the Newcastle Stage occurred during brief periods of calm, alternating with rapid deposition, due to rejuvenation of the drainage and flooding of the basin. Conditions gradually became less vigorous as the land surfaces were reduced almost to base-level.

At the close of Permian time, there appears to have been renewed elevation of surrounding lands, which produced the Narrabeen Beds of the Triassic.

The author, having studied certain palaeogeographical problems in connection with the distribution and origin of torbanite deposits, suggests the following conclusions:

The Upper Marine and Upper Coal Measure sediments, occurring in the North-Western Region, accumulated in a north-western extension of the main area of deposition in the South-Eastern Region. As far as can be ascertained, the Upper Coal Measures in the North-Western Region represent the Newcastle Stage; and it seems highly probable that the coal-forming swamps of the Tomago Stage did not extend to the north-west for any appreciable distance beyond the limits of the present Hunter Valley. The Permian sediments of the North-Western Region were warped by later earth-movements, so as to be included in the Oxley Basin and the south-eastern margin of the Great Artesian Basin. Mesozoic sediments were deposited in these basins, covering the Permian strata with thick beds of Triassic and Jurassic rocks. Owing to the lack of recent uplift and dissection, the Permian beds, to a large extent, still remain buried.

The Upper Marine beds in the North-Western Region consist of coarse sandstone, conglomerates, tillites and boulder beds. They are continuous, through the Gulgong-Ulan-Rylstone districts, with the Upper Marine outcropping along the western side of the South-Eastern Region; but marine fossils are generally absent. Possibly, some of these deposits may represent freshwater, fluvio-glacial sediments, contemporaneous with the true marine beds of the South-Eastern Region. The absence of Tomago coal-measures, along the western side of the South-Eastern Region and also in the North-Western Region, means that a considerable time-break must have occurred in these areas, between the close of Upper Marine deposition and the development of Newcastle coal-measures. During this interval, the area of sedimentation moved to the east, where Tomago coal-measures accumulated. It follows that certain areas, where Newcastle measures lie directly on the Upper Marine, must have remained more or less stable during the time-break, as depression or elevation would have resulted in deposition of Tomago beds, or wide-spread removal of Upper Marine strata, respectively. Evidently, considerable quantities of sediments were transported across these areas, to be deposited further to the east as the Tomago beds. This suggests that recession of the sea, at the close of Upper Marine time, left the marginal Upper Marine sediments stranded slightly above or at the base-level of sedimentation; and that the rivers, which had supplied their sediments, passed over the marine beds by cutting shallow channels and delivered sediments to the area in which Tomago measures were deposited.

Coal-forming conditions, within the North-Western Region, appear to have resulted from the fact that a slight depression brought the stranded Upper Marine beds once again within the area of sedimentation; and Newcastle coal-measures were deposited. The measures so formed were relatively thin, and appear to have been deposited in shallow, swampy areas. Outcrops, available along the eastern and south-western margins of the North-Western Region, indicate that the coal-measures are continuous, although variable in thickness. Conglomerates and coarse sandstones are generally absent from the measures of the North-Western Region, with the exception of the eastern shore-line deposits between Murrurundi and Gunnedah, where coarse sediments are common. This suggests that country of low relief prevailed to the north, west and south-west, with high land to the east.

In view of the foregoing palaeogeographical considerations, it is possible to draw the following conclusions, of importance concerning the distribution of torbanite deposits:

1. Conditions of general quiescence prevailed throughout the deposition of the Tomago coal-measures, the sediments being supplied by sluggish rivers from country of low relief.

2. During the deposition of the Newcastle coal-measures in the South-Eastern Region, sediments were supplied by active mountain streams, subjected to periodic rejuvenation and flooding. This would give rise to large supplies of freshwater round the margins of the basin, while more sluggish conditions would exist in the central portions.

3. Deposition of Newcastle coal-measures in the North-Western Region was accomplished under moderate conditions involving slow transport of sediments, similar to the accumulation of the earlier Tomago measures. Only slight sinking of the area occurred. There is no evidence of the periodic rejuvenation and flooding which took place in the South-Eastern Region.

4. The marginal sediments, produced under vigorous conditions along the western side of the South-Eastern Region, are unique: similar sediments, formed along the eastern side, having been submerged by the Pacific Ocean, and those of the northern side having been removed by erosion.

Correlation between Distribution of Torbanite Deposits and Regional Conditions of Upper Coal Measure Deposition.—The vigorous marginal conditions of sedimentation, which produced the coal-measures along the western side of the South-Eastern Region, may be correlated with the confinement of torbanite deposits to the western margin of the Newcastle measures. Conversely, the absence of deposits in the North-Western Region can be correlated with the conditions of general quiescence, under which the measures were laid down. Similarly, the more sluggish conditions, which must have existed during the deposition of the central portions of the Newcastle coal-measures in the South-Eastern Region, appear to have resulted in the absence of torbanite. The same feature applies to the Tomago coal-measures, which were deposited under conditions of quiescence, and do not contain torbanite deposits. Furthermore, the occurrence of only one deposit above the No. 3, or Dirty Coal Seam, and the complete absence of deposits above the No. 2 Coal Seam, within the torbanite-bearing area of the Newcastle Stage, can be correlated with the fact that conditions of sedimentation became less vigorous towards the close of Upper Coal Measure deposition.

The correlation of vigorous marginal conditions of coal-measure deposition and rapid transport of sediments, with the formation of torbanite deposits, requires an explanation to show how these conditions could control the development of torbanite. Such an explanation may be found in the influence of decaying vegetation on the growth of the alga, and the facilities provided for the development of algal sapropel by the specialized marginal environment of sedimentation.

A characteristic feature of torbanite is the absence of vascular-plant remains, in particular the dark brown jelly or ulmo-humic, colloidal derivative produced by the decay of vascular plants. This substance gives a brown colour to water, in which plant material is decaying, and permeates the fibrous plant debris of peat, where it forms a stiff jelly when sufficiently concentrated: it is the dark brown groundmass of most coals and cannels, and constitutes the principal substance of structureless vitrain. Only in rare cases (material transitionary between torbanite and coal) has any of this humic product been found in association with the algal sapropel of torbanite.

It is evident that conditions, favouring accumulation of humic product and development of the alga, are mutually exclusive, or else the humic product prevents the growth of the alga. Both factors are probably involved, but the latter would seem to be the most important for the following reasons:

1. High concentrations of the humic product would prevent aeration of the water, and deprive the alga of oxygen and carbon dioxide.

2. The humic product contains humic acids, which react with the minerals dissolved in the water and precipitate insoluble humates. This would deprive the alga of its supplies of dissolved mineral matter, which is essential to its growth.

3. The precipitation of humates may form a flocculent coating on the algal colonies, preventing their normal development and respiration.

4. The brown coloration of the water, due to the presence of humic product, would reduce the amount of sunlight available to the alga.

5. The humic product may be toxic to the alga, in a manner similar to the toxic effect it is believed to have on bacterial decay of vascular-plant material.

The relations between the conditions of coal-measure sedimentation, quantity of humic product in the water, and the development of the alga, must be taken into account, at this juncture, to explain the correlation of torbanite-formation with vigorous marginal conditions of sedimentation. Details of the local environment, required for the formation of algal peat, are treated fully later in the paper. It is sufficient, for the present discussion, to infer that the deposits were formed in small, isolated lakes, filled by the penetration of backwaters through peat beds or marshes from flowing watercourses some distance away.

The presence of lenticular deposits of torbanite, cannel coal, clay shales and other accessory materials on the main coal-bearing horizons in the Upper Coal Measures indicates shallow-water conditions, with the surface of sedimentation only partially covered by water, rather than the deposition of the coal-forming debris in large, completely submerged areas. Large rivers, bringing water and sediments to the regions of sedimentation, must have passed across the marginal areas in wide, meandering watercourses of ever changing form, with banks of peat and sub-aerial swamp-vegetation. Towards the central portions of the basin, these watercourses dispersed by means of distributaries, and eventually became lost in swampy areas and peat bogs. Isolated lakes would be formed in marginal areas by the washing out of peat bogs, and meanders being cut off during periods of flood. Similar lakes were formed, less frequently, in the central areas by unequal deposition of sediments from floods, and lowering of the general water-level during normal periods. Such lakes, both marginal and central, received supplies of water by percolation through peat beds and marshes from the main channels of moving water. In marginal areas, the water, penetrating to the isolated lakes, would be comparatively fresh from the mountain streams, and would carry dissolved gases and mineral matter, but would not have been in contact with the decaying vegetation of peat bogs long enough to become heavily charged with humic product. This provided the necessary physical as well as chemical environment for the formation of algal sapropel.

The isolated lakes in the central areas would receive supplies of stagnant water, poorly aerated and containing a high concentration of humic product, gathered during its passage through, perhaps, fifty miles of decaying vegetation. These conditions, accompanying sluggish deposition, are most unlikely to have supported an abundant growth of the alga, for reasons already given; and it is considered that, in Upper Coal Measure time, they were the principal factors determining the absence of torbanite deposits in the whole of the North-Western Region, the whole of the Tomago Stage, the central portion of the Newcastle Stage in the South-Eastern Region, and the top of the marginal facies of the Newcastle Stage in the Western and South-Western Coalfields.

It is suggested, therefore, that the formation of torbanite was confined to the margin of the Newcastle coal-measures along the western side of the South-Eastern Region, owing to the development of isolated lakes filled with backwaters, containing a low concentration of humic degradation products, having soaked through peat beds and swamps from channels carrying fresh, aerated water of mountain streams.

Distribution of Torbanite and Conditions of Sedimentation in the Lower or Greta Coal Measures.—The Lower or Greta Coal Measures of the Northern Coalfield were deposited in an elongated trough, crossing the present coast-line in the vicinity of Newcastle and passing inland to the north-west, probably, to Gunnedah. The measures are relatively thin, but contain one important coal-bearing horizon, on which the Greta Coal Seam is situated. Torbanite occurs as thin, irregular bands, in the Greta Coal Seam, at various points along the outcrop of the measures, from Murrurundi in the north-west through Muswellbrook to Greta, Maitland and Cessnock in the south-east.

The Greta measures extend considerably beyond the limits of Lower Marine deposition, particularly to the north-west, indicating the development of low lands to the north-west of the area occupied by the Lower Marine sea. Probably most of the Greta measures were laid down under conditions of general quiescence; but marginal conglomerates, described by Raggatt (1938), occur along the north-eastern shore-line, and pass into sandstone towards the centre of the basin. These marginal facies suggest that high lands existed to the north-east, and that conditions of vigorous deposition occurred along the north-eastern shore-line. The outcrops of the Greta Coal Seam, containing torbanite, are situated along the north-eastern side of the area of deposition, suggesting a correlation between torbanite-formation and specialized marginal sedimentation, similar to the correlation already described in the case of the Upper Coal Measures.

The central portion and south-western margin of the Greta Coal Measures do not outcrop; and it is not known whether the occurrence of torbanite is confined to the north-eastern margin, or not. Thus evidence regarding distribution of torbanite in the Greta measures is incomplete; but its occurrence in the outcrops along the north-eastern margin is compatible with the hypothesis requiring special marginal conditions for torbanite-formation.

Greta Coal Measures, containing torbanite, were also deposited in small lakes in the Clyde River district. The coal-forming environment, which existed in this small lake-area, no doubt involved conditions approximating to marginal sedimentation, as large central areas of sluggish deposition and stagnant water would not have been present.

It may be concluded that evidence from the Greta Coal Measures supports the conclusions with regard to palaeogeographical control of torbanite-formation in the Upper Coal Measures; but the evidence is incomplete and can not be regarded as conclusive.

Evidence from the Formation of Recent Algal Sapropel.

The geological history and structure of the Coorong region, South Australia, has been described briefly by Mawson (1938). The Coorong is a narrow strip of salt water, ninety miles long. It communicates with the ocean at the mouth of the Murray River, from which it runs in an easterly direction, parallel to the coast, while a coastal dune separates it from the open sea. The adjacent, low-lying country on the northern side of the Coorong is known as the Coorong region. It consists of late Tertiary to Recent sediments, lying almost horizontally on an old basement of Pre-Cambrian and early Palaeozoic rocks. The basement was reduced to a peneplain by early Tertiary time, and was tilted to the south by Miocene movement which brought it below sea-level, and resulted in the deposition of Miocene and early Pliocene marine sediments, before it emerged in middle Pliocene time (Mawson, 1938).

The country, reclaimed from the sea by slight late-Tertiary elevation, is now the low area in which coorongite forms. The area is only slightly above sea-level, and its drainage is partially held up by calcareous sand-dunes. This results in the formation of swamps, lakes and pools, varying from fresh-water to saturated brine. Many of the swamps and small lakes are filled during seasons of excessive rainfall, but at other times are dry. Some of these are filled by direct run-off during wet seasons, and others by back-waters from channels communicating with the Coorong. Several of the permanent lakes are inhabited by different kinds of microscopic algae and other organisms, giving green, blue and purple colours to the waters. In the spring of 1939, the writer observed several lakes with a greenish hue, due to the presence of *Botryococcus Braunii*, while others possessed bluish-green and reddish colours. It appears that *Botryococcus* is present every year in some of the lakes, but only occasionally in sufficient abundance to form deposits of coorongite.

The conditions required for maximum development of the alga seem to have existed in temporary lakes, filled by the flooding of main drainage channels in the area. A dry lake, in which coorongite had previously formed, was examined in some detail. It consisted of a small basin-like feature, with a depth of about fifteen feet, and an average width of about sixteen chains, as illustrated by the section in Fig. 4. The surrounding country was covered with dense scrub, terminating abruptly at the margins of the lake, the shore-line of which, for the greater part, was well defined by a comparatively steep profile. The lake-floor consisted of Tertiary limestone, covered with sandy soil a few inches to several feet in thickness (Fig. 4). One section of the shore-line was very low, with scrub growing practically at the level of the lake-floor, and from this point, low scrub-covered land extended to a neighbouring lake connected by means of a swampy channel to a nearby creek. Evidently flood-waters from the creek had "backed up" into the first lake, and then found their way through low, scrub-covered land to the second lake, where coorongite had formed as a result of phenomenal algal growth.

Lakes, carrying large stocks of *Botryococcus* in 1939, were isolated from the main water channels by dunes or swampy areas with sub-aerial vegetation. The formation of coorongite in 1919 was described as occurring in "shallow ponded flood-waters" (Mawson, 1938). The existing lakes, carrying stocks of *Botryococcus*, contain but little sub-aerial swamp-vegetation of a vascular nature, and the dry beds of those in which coorongite had formed are free from terrestrial plants. Filling of the lakes has occurred sufficiently to prevent the establishment of terrestrial plants, and, when filled, the water is usually too deep to allow the growth of sub-aerial plants.

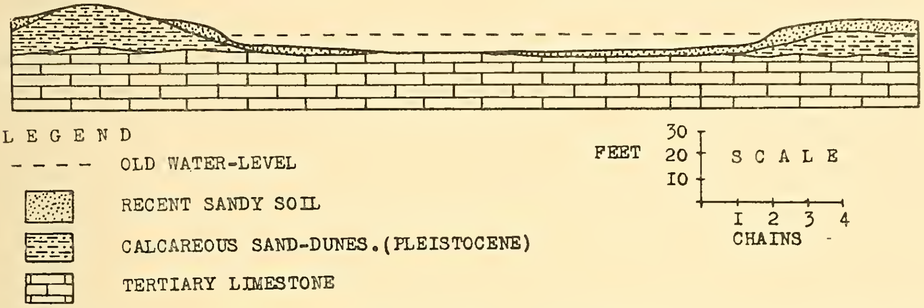

Fig. 4.—Generalized geological section across a "coorongite lake" in the Coorong region, South Australia.

Conditions, favouring maximum growth of the alga and subsequent formation of coorongite, would appear to exist when comparatively fresh flood-waters, having deposited most of their sediment, migrate through swamps and scrub-covered dunes into a dry depression, free from permanent terrestrial flora and possessing no definite outlet, through which the impounded waters can escape. The newly-formed pond would be free from currents which, under other circumstances, would remove the alga as it developed; the water would be well aerated, and contain sufficient humic degradation product to supply available nitrogen for the alga, but insufficient to interfere with its growth. Fine suspended sediment, remaining in the water after its infiltration to the pond, would slowly settle during the early stages of algal development, leaving only dissolved mineral matter to be assimilated by the alga. Low, dense scrub, surrounding the pond, would allow a maximum amount of sunlight to enter the water, and also shield it from excessive wind, which may cause disturbing wave action. Such conditions, following the cold, wet winter of the Coorong region, could be expected to promote vigorous growth of *Botryococcus*, which is an alga of temperate climates.

The first evidence of excessive development of the alga is the formation of a scum on the surface of the water. This was described by Blackburn (1936) in a laboratory culture, and by Mawson (1938) in connection with the 1919 development of coorongite in South Australia. The scum appears to be formed by dead algal colonies which have risen to the surface owing to the development of gas bubbles from the decaying cells. After complete decomposition of the cells, the decay-resisting substance of the cell cups and thimbles coalesces to form the tough, rubbery mass of coorongite, which remains on the bed and sides of the depression after the water has receded.

The lake areas of Gippsland and south-western Victoria are said to be somewhat similar, geographically, to the Coorong region; but evidently the particular set of conditions, favouring the development of *Botryococcus* in the Coorong lakes, does not occur there, as excessive algal growth and the occurrence of coorongite, as far as can be ascertained, have not been reported.

Formation and Preservation of Permian Algal Sapropel.

Accumulation.—The local conditions, favouring the accumulation of algal sapropel in Permian time, can be deduced from evidence obtained in the study of the formation of recent algal sapropel or coorongite, and the palaeogeographical data concerning the distribution of torbanite in the Kamilaroi coal-measures. This evidence, detailed under previous headings, suggests the following environmental factors:

1. High country existed along the north-eastern side of the trough, in which the Greta Coal Measures were deposited, and the western margin of Upper Coal Measure deposition in the area of the Western and South-Western Coalfields.

2. The high lands provided rivers carrying large quantities of water and sediment.

3. The sudden change, in gradient and transporting power of the rivers at the shore-lines of coal-measure deposition, resulted in unequal distribution of sediments in marginal areas.

4. Excess sediments, dropped by the rivers, produced an uneven surface of sedimentation at, or slightly above, water-level in marginal areas.

5. On reaching the shore-lines, the rivers became large, meandering watercourses, passing towards the central regions of sedimentation, where the mean water-level was probably higher than the surface of the sediments.

6. Frequent flooding of the rivers and marginal areas occurred.

7. Isolated lakes of temporary nature were formed in marginal areas by uneven deposition of excess sediments, the washing out of peat bogs and silt beds, and the development of "cut-off" meanders belonging to the main watercourses.

8. The isolated lakes received supplies of water from the main channels by infiltration through swamps, peat beds, sand dunes, and silt beds.

9. Fluctuations in the water-level, due to variations in the volume of water delivered by the mountain rivers, caused alternate filling and emptying of the lakes, preventing the permanent establishment of either swamp or terrestrial vegetation.

10. The water, penetrating to the lakes, was well aerated, and carried fine, suspended sediment, dissolved mineral matter, and only small quantities of humic products of decaying vegetation.

11. The lakes, when filled, were suitable for the abundant development of the Permian ancestor of *Botryococcus Braunii.*

Some torbanite deposits possess floors of coal, indicating that the original algal lake had existed in a depression or washout in a peat bed. The torbanite is frequently separated from its coal floor by a thin, clay band, which means that fine sediment, brought in with the water, had time to settle before algal development commenced. Many deposits have floors of clay shale, while others lie upon sandstone. In these cases the algal lakes must have existed on beds of silt or sand formed by earlier floods.

The recent formation of coorongite, by surface accumulation of decomposing alga, produces masses of sapropel, in which the colonies are fused together without intervening, inorganic matrix. Similar sapropel existed as the original debris of some torbanites, in which there is no continuous skeleton of inorganic matrix. In such cases, the algal debris probably accumulated at the surface, until decomposition of the cells was complete, came to rest at the bottom of the lake—either by virtue of its density, or by the recession of the water—and was eventually buried. Most torbanites, however, possess larger amounts of inorganic matrix embedding the colonies, which suggests that the algae accumulated on the bottom of the lake to form a bed of sapropel containing evenly distributed sediment. This would be expected to occur if small amounts of fine sediment were introduced during the periods of algal development. These sediments would sink the colonies and entomb them on the lake-floor. Such introduction of sediment was probably effected by continuous infiltration of water at one side of the lake, and its slow escape through another, or the floor, without causing sufficient current to upset the settling of fine sediment. Vertical variation in the amount of inorganic matrix is common. This could be caused by repeated flooding of the main watercourses, giving fluctuation in the amount of introduced sediment, or possibly, by variations in climatic conditions influencing the rate of algal development.

The torbanite deposits consist of either one layer of torbanite, or several well-defined layers, from a few inches to several feet in thickness, separated by bands of cannel coal, or clay shale. The author believes that each layer of torbanite was built up by no more than one annual period of algal growth. The following are the reasons supporting this belief:

Periodic seasonal growth is certain to have occurred, as all microscopic algae possess well-marked maximum and minimum phases of annual development (Chapman, 1941).

All separate periods of growth must be marked by some banded feature. The deposition of sediment, which occurred during algal growth, must have continued, to a greater or smaller extent, in the absence of the alga, giving rise to a clay shale band—if no plant debris were introduced. Any vascular-plant material—either indigenous, drifted or wind-borne—introduced during the absence of the alga, would mingle with the inorganic sediment to form cannel coal. If the water receded from the lake, during the season in which the alga ceased to grow, some wind-blown debris or surface-oxidation effect would be certain to produce a band or break in vertical continuity. Some feature, however small, would have been formed, as all the natural factors of sedimentation would tend to produce a line of demarcation between the seasonal periods of algal growth. Quite possibly, a sudden change in some factor may have produced a banded feature in the sapropel from one season's growth, in which case the layers of torbanite would be equivalent to less than one year's accumulation. Thus, it appears evident that each uniform layer of torbanite must represent part or whole of one season's growth, and can not be the accumulation of several seasons.

Homogeneous layers of torbanite two feet in thickness, without any break in vertical continuity, are known to occur in some deposits. This introduces the question of compression, and the original thickness of algal sapropel required to give such layers, which, in view of the foregoing, were probably built up during one season. The living algal colonies were globular or more or less spherical; but the fossil colonies in torbanite are flat, disc-shaped bodies, for which the ratio of width to thickness averages about 6 to 1. The ratio for dead algal colonies, in coorongite which has not been compressed at all, is about 2 to 1, due to collapse after death. The increase in the ratio from 2 to 1, to 6 to 1, is evidently due to compression after burial under superimposed sediments. Most torbanites contain very little inorganic matrix separating the fossil colonies, and the increase in the ratio of width to thickness of the discs, after burial, appears to be a true measure of the extent to which the original layers of algal sapropel were reduced in thickness by compression. The average increase in the ratio from 2 to 1, to 6 to 1, means that the layers were reduced to three-eighths of their original thickness, or that a layer of torbanite, 1 foot in thickness, represents an original layer of algal sapropel 2 feet 8 inches in depth, or that the thick, homogeneous layer of torbanite, amounting to 2 feet, would indicate a bed of sapropel originally 5 feet 3 inches deep. These compression ratios are lower than those calculated for coal (Raistrick and Marshall, 1939), as would be expected, owing to the greater compressibility of a spongy, fibrous, coal-forming peat, compared with the compact mass of algal sapropel.

The eukerogenic and dyskerogenic forms of algal sapropel, previously described (Dulhunty, 1943*a*), appear to have originated during accumulation. A possible explanation of the differentiation into the two forms is to be found in the following facts: The fatty substance of the cups, in algal colonies, represents excess food supplies secreted by the cells (Chapman, 1941). Variations in the relative amounts of material, derived from fatty cups and cuticular thimbles, have been noted in living colonies (Blackburn, 1936). Such variations probably depend on environment: favourable conditions cause secretion of large quantities of fatty substances which, on distillation, give higher oil yields than the material of the thimbles. Thus, it is possible that optimum conditions of growth give rise to eukerogenic sapropel, while an unfavourable environment produces the dyskerogenic form. The greater depth of colour, possessed by the latter, is probably due to the secretion of excess pigment, under unfavourable conditions of growth; and other properties (colour of streak, colour of fracture surface, optical density, ratios of volatile/fixed carbon, oil/organic matter and oil/gas), characteristic of the two forms after transformation to torbanite, are undoubtedly related to the intrinsic nature of the substances constituting the cups and thimbles.

Preservation.—One of the outstanding properties of algal sapropel, formed from the remains of *Botryococcus Braunii*, is its remarkable resistance to weathering and decay. Masses of coorongite, collected from dry lake-beds in the Coorong region, have withstood desiccation and the effects of wet conditions for periods of from ten to twenty years. The only changes wrought by such exposure are increases in hardness, toughness, and depth of colour. The elasticity, bright lustre, lightness of streak, and hydrocarbon affinities remain. The substance of the sapropel is particularly immune from oxidation as well as bacterial attack. Micro-sections, cut across the surface of coorongite exposed to atmospheric weathering for about twenty years, show an opaque, brittle, oxidized surface of no more than one millimetre in thickness. Other masses of coorongite, partially buried in moist soil, have not yielded to bacterial decay. These properties are probably due to the fact that the living algal cell secretes about itself a fatty cup and cuticular thimble designed to give protection from desiccation and bacterial attack for several years, while in the resting stage awaiting favourable conditions for growth.

Preservation of ordinary coal-forming peat depends on the prevention of natural oxidation and bacterial decay. Oxidation and the action of aerobic bacteria must be prevented by a covering of stagnant water, silt or organic debris. The action of anaerobic bacteria must be controlled by the formation of toxic products. The preservation of algal sapropel is relatively simple, compared with that of coal-forming peat, as natural resistance to decay and oxidation allow it to await burial for long periods of time, without special conditions of preservation. The rarity of occurrence of torbanite in the coal-measures of the world can not be due to difficulties in preservation, but rather to the very special conditions required for abundant algal growth.

Burial.—The predominance of inorganic sediments in the New South Wales coal-measures, even on the coal-bearing horizons in marginal areas, indicates frequent and widespread deposition of silt and sand over the area of sedimentation. Under such conditions, the probability of the burial of algal sapropel, within a period of from twenty to thirty years after formation, would be great. A minor change in the course of a main channel near the algal lake, or the spreading of silt and sand beds by an unusually large flood from adjoining high lands, would effect the burial of the algal sapropel, and give the clay shale or sandstone strata which commonly form the roofs of torbanite deposits.

Burial under organic debris also occurred, giving coverings of coal and cannel. This resulted, no doubt, from the establishment of vascular swamp-vegetation, caused by the lakes becoming shallower, or the entry of a flowing stream carrying vascular-plant debris.

Once covered, the algal beds would remain indefinitely, to be slowly changed by metamorphic processes into the torbanite deposits of today.

METAMORPHIC EVOLUTION OF THE TORBANITE DEPOSITS.

The simple subsidence and elevation, to which the coal-measures of the Western and South-Western Coalfields have been subjected, would be unlikely to have had any special metamorphic effect on the torbanite deposits. The warping, which occurred in the Greta measures of the Northern Coalfield, and the strong faulting along their north-eastern margin appear to have had little effect on the torbanite—apart from the development of occasional slickenside faces and local shear-zones. The principal factors, causing metamorphic evolution of torbanite, were pressure from overlying strata, geological time and moderate earth temperatures.

Conditions of Metamorphism.

An attempt has been made to estimate the approximate conditions of pressure and temperature to which the torbanite deposits have been subjected during consolidation. Owing to the complex nature of such problems, the estimates are necessarily very approximate, but they have been made with the object of indicating the order of magnitude of the factors involved.

Pressure.—In the estimations of rock pressures in connection with the study of isostasy, it is usual to assume that differential pressure is equivalent to about 25 per cent. of the total hydrostatic pressure, owing to the rigidity of the rocks and the necessity of overcoming the resistance equal to the forces required to cause shearing movement. On this basis, the differential pressure exerted by a column of rock in a downward vertical direction would be no more than 25 per cent. of the weight of the column, owing to the reaction with the adjoining columns, which are supported by the basement. It would appear, however, that this principle would not apply to the present problem, as the torbanite deposits are interbedded with coal and other sediments extending over a large area, and constituting a stratum which would yield to vertical compression as much as, if not more than, the deposits of torbanite. This means that the overlying strata would not be supported by rocks surrounding the deposits, and the columns of rock, above each deposit, would not be held up by reaction with the adjoining columns.

The overlying strata would be supported by basement rocks only at the margins of the basin of deposition, and the area of this basin was very large, while the thickness of the overlying rocks was relatively small. Thus, the influence of the marginal support, depending on the rigidity of overlying rocks, would be negligible. It follows that the weight of overlying rocks would act as a vertical compressional force, which, within any small area of the torbanite-bearing stratum, would be equal to the total weight of the column of rock immediately above the area concerned. Each deposit may be considered a small area within the compressible stratum, and the compressional force, to which the torbanite has been subjected, may be calculated from the total weight of rock overlying the deposit.

In the case of deposits occurring in the Upper Coal Measures of the Western and South-Western Coalfields, the maximum depth of cover, existing before uplift and erosion, varied considerably, increasing with the distance from the old shore-line. It is probable that some of the deposits nearest the shore-line, such as that of Tong Bong Mountain, were covered by no more than 100 feet of coal-measures and 500 feet of Triassic sandstone. Others, further from the shore-line, including Baerami and Glen Davis, appear to have been buried beneath 150 to 300 feet of coal-measures, and as much as 2,000 feet of sandstone. In estimating maximum pressures to which the deposits may have been subjected, the overlying strata must be considered to have been saturated with water, at the time when subsidence of the area of deposition ceased. The average weight per cubic foot of sandstone is about 160 lb., and for shale about 170 lb. A reasonable figure for the porosity of the Triassic sandstone would be about 7 per cent., and for coal-measure shales, about 1 per cent. Therefore, the weight per cubic foot of saturated sandstone could be taken as 164 lb., and for shale 171 lb.

Assuming an average cover of 100 feet of shale and 500 feet of sandstone, for deposits nearest the old shore-line, the maximum weight per cubic foot on the torbanite would have been in the vicinity of 99,000 lb., representing compressional force or pressure of approximately 690 lb. per sq. in. Deposits furthest from the shore-line, with an average cover of 200 feet of shales and 2,000 feet of sandstone, were probably subjected to a pressure of the nature of 2,500 lb. per sq. in. Thus, it appears that the maximum pressures endured by the torbanite deposits of the Western Coalfield varied from about 700 to 2,500 lb. per sq. in.

In the Greta Coal Measures of the Northern Coalfield, the maximum depth of cover is very difficult to estimate, owing to contemporaneous warping and erosion, and the complete removal of Triassic beds from the greater part of the area in which the Greta measures outcrop. In the Hunter Valley area, Upper Marine beds vary from 3,000 to 4,000 feet; Upper Coal Measures from 2,000 to 3,000 feet; and the Triassic, now removed, probably amounted to, at least, 1,500 feet. It seems reasonable to assume a maximum cover of, perhaps, 7,500 feet, composed of sandstone, conglomerate, shales and tuffaceous rocks. These strata were probably equivalent to about 3,000 feet of shale and 4,500 feet of sandstone, representing a pressure of 8,700 lb. per sq. in. The cover was much less towards the north-west, and, probably, the pressure on the torbanite, in the vicinity of Murrurundi, did not exceed the pressures estimated for the Upper Coal Measures in the Western and South-Western Coalfields.

It is evident that the pressures have been relatively moderate. The probable maximum of 8,000 to 9,000 lb. per sq. in. can not be considered very great, compared with pressures of 30,000 to 40,000 lb. per sq. in. used in modern hydraulic presses for moulding and consolidating materials. Pressures as high as 280,000 lb. per sq. in. have been used in experimental work on the consolidation of peat (Stevenson, 1916).

Temperature.—The maximum temperature to which the deposits have been subjected is a matter of considerable speculation, although it can be shown, with a reasonable degree of certainty, that the average temperatures have been very moderate. The progressive sinking of the area of Kamilaroi deposition, from Carboniferous to Triassic time, probably resulted in a depression of the geo-isotherms; but the still-stand in the latter part of Mesozoic time, and the elevation of the Tertiary period no doubt allowed them to rise.

Temperature gradients have been determined in deep bores and shafts put down through the Triassic sandstone into the Upper Coal Measures in the Sydney district (David and Pittman, 1893, 1894; Rae, Pittman and David, 1899). The results of these determinations show that the rate of increase of rock temperature downwards, at Cremorne and Balmain, averages about 1°F. for every 85 feet, commencing with a mean surface temperature of 63°F. The Sydney district is situated in an area which was only slightly uplifted by Tertiary elevation. The upper portion or Wianamatta Stage of the Triassic is little above the present sea-level at many places, and the Kamilaroi beds, now 3,000 feet below sea-level, can not be far removed from their original position, when subsidence and deposition ceased at the close of Triassic time. Assuming that the geo-isotherms have risen slightly during the latter part of Mesozoic time and the Tertiary Era, it is reasonable to take the present sub-surface rock temperature in the Sydney district as the average maximum temperature to which the Kamilaroi strata have been subjected. On this basis, it is probable that the torbanite deposits of the Greta Coal Measures have not been heated above 150°F., while those of the Upper Coal Measures have probably not exceeded 100°F.

Certain portions of some torbanite deposits may have been heated to temperatures much higher than those estimated above, owing to their proximity to igneous intrusions, but such heating has been very local; and in no case can it be considered to have influenced the metamorphism of the whole of any one deposit. The average, maximum temperature of 150°F. is very moderate, and such heating, at atmospheric pressure, has no apparent effect on either coorongite or torbanite. Apparently, rock temperatures have not played an important part in the transformation of coorongite to torbanite.

Time.—As the torbanite deposits are of Permian age, the time factor is very great, and appears to have been the most important feature in the metamorphism of algal remains, providing opportunity for chemical and physical changes to occur at a rate which would be considered negligible under laboratory conditions.

Physical and Chemical Changes.

The main physical changes, accompanying the formation of torbanite from the original algal deposits, involve increase in hardness, reduction in elasticity, production of a compact and homogeneous texture, slight increase in depth of colour, and development of a tendency to split in a direction parallel to the bedding plane. Properties, remaining more or less unchanged, include specific gravity, colour of streak, lustre, and conchoidal fracture in directions oblique to the bedding. Certain optical changes occur, such as increase in refractive index of the algal material, increase in optical density, and development of anisotropism including "polarization laminae".

Chemical changes taking place during the transformation of the algal remains are of considerable importance. The ultimate and proximate compositions of coorongite and torbanite, of about the same ash content, are indicated in Table 1. A marked decrease occurs in oxygen content, and a slight reduction in the amount of hydrogen, with a corresponding increase in carbon content. Proximate analyses show reduction in hygroscopic moisture and considerable increase in the volatile/fixed carbon ratio.

TABLE 1.

Ultimate and Proximate Compositions Typical of Coorongite and Torbanite.

Material.	Ultimate Composition.				Proximate Composition.			
	C.	H.	O.	N.	H_2O.	Vol. Cont.	F. Carb.	Ash.
Coorongite	78·4	12·0	8·9	0·7	1·7	80·3	7·0	11·0
Torbanite	85·0	10·0	4·3	0·7	0·5	75·0	13·0	11·5

Changes in ultimate and proximate compositions indicate a process of slow carbonization, somewhat similar to, but far less marked than, coalification of peat, which involves elimination of much greater quantities of oxygen.

Organic matter of coorongite consists of natural oils, fatty materials and small quantities of carbohydrates, much of the material being soluble in organic solvents. After transformation to torbanite, the organic matter is completely insoluble in common organic solvents at their boiling-points under atmospheric pressure. Recent experimental work, carried out by the writer (Dulhunty, 1942*b*, 1942*c*, 1943*b*), has shown that the organic matter can be rendered soluble by heating at temperatures between 280° and 340°C., which are lower than those causing thermal decomposition, and that the change to the soluble form does not involve evolution of volatiles or gas-formation. Soluble products, thus formed, are very heavy hydrocarbons, which can be converted to paraffins and olefines by thermal cracking.

The conversion of the organic matter to the soluble form by heating appears to be a kind of depolymerization, and it is accompanied by the development of a soft, "rubbery" condition, closely resembling the pliable nature of organic matter in coorongite. The soluble product of heated torbanite contains less oxygen than the substance of coorongite, owing to elimination of this element during natural carbonization. Apart from deficiency in oxygen, which enhances its hydrocarbon properties, the product is similar, in its empirical chemical composition, to the original algal remains in coorongite. These facts suggest that the change from coorongite to torbanite involves a polymerization process, which slowly reduces solubility and increases hardness of the organic matter, and that the effect of heating torbanite is to reverse the process, causing depolymerization, which increases solubility and reduces hardness.

Oxidation of coorongite and torbanite with hot nitric acid gives oxidation products of the nature of fatty acids, which appear to be generally similar, although detailed chemical work has not been carried out along these lines.

Evidently, the most important chemical changes involved in the transformation of coorongite to torbanite have been of the nature of molecular rearrangements and structural modifications, rather than fundamental changes in chemical composition.

Certain inorganic chemical changes have also occurred during the formation of torbanite. Chalcedonic silica frequently occurs within the gelosite and retinosite bodies. Its occurrence has been studied by the writer (Dulhunty, 1939*a*), and it has been shown that silica has replaced the organic matter, giving rise, in some cases, to siliceous torbanites of no commercial value. The fact that siliceous replacements take the form of the flattened, disc-shaped bodies means that invasion by siliceous waters occurred after preliminary burial and slight compression; but it is highly probable that it was early in the metamorphic history, while the organic matter was still soft and small cavities remained, as replacement would be unlikely after the hard, compact gelosite and retinosite had been formed. Variations in hardness of the inorganic matrix, in torbanites containing appreciable amounts of silt, indicate different degrees in cementation, resulting from inorganic reactions similar to those which accompany the consolidation of clay shales.

Metamorphic History.

As already stated, a thin covering of sediment was sufficient to prevent atmospheric oxidation and bacterial decay. With continued subsidence, the deposits of algal sapropel were rapidly covered by greater thicknesses of sediment, protecting them from contemporaneous erosion which would be likely to occur at the surface. Soon after burial, the organic matter probably commenced to undergo a process of slow polymerization, the molecules of oil and fatty substances forming large, condensed ring-structures.

During the earlier stages of transformation, circulating ground-waters, charged with dissolved mineral matter, permeated the deposits, causing cementation of the inorganic matrix and effecting replacement of varying quantities of organic matter by silica. As greater thicknesses of strata accumulated above the deposits, pressure gradually increased, helping to consolidate the algal remains into a compact mass, and driving out excess water. With continued polymerization, the organic matter became less soluble and, probably, more resistant to attack from inorganic solutions. It also became harder and commenced to lose its elasticity, although an extraordinary degree of toughness remained. In addition to molecular rearrangement, the process of natural carbonization commenced to eliminate oxygen and small amounts of hydrogen from the condensing molecules, but less rapidly than in the case of coal-formation, due to early polymerization and stability of the algal substance. This, possibly, contributed to the high oil-producing properties of torbanite.

Continued sinking of areas of deposition built up great thicknesses of overlying strata, and pressure on the deposits commenced to reach the maximum, amounting from 5,000 to 9,000 lb. per sq. in. in some cases; but the algal matter must have been hard and very tough at this stage, as there is no evidence of torbanite having been forced into fissures, veins or sills. Earth temperatures, amounting to, perhaps, 150°F. in the Greta Coal Measures, were insufficient to play any important part in metamorphism, and would not even affect the moisture content, under existing pressures. It is probable that the relatively low temperatures allowed polymerization to proceed without excessive carbonization.

Having reached the stage of hard, compact material under pressure, the deposits attained an extremely stable condition; and further polymerization and carbonization must have proceeded at a very slow rate. Probably the deposits in the Greta measures reached this stage by the end of Permian time, and Upper Coal Measure deposits during the latter part of the Mesozoic Era. The slow rate of change, in advanced stages of metamorphism, is evident from the fact that torbanites of the Greta and Upper Coal Measures are almost identical in their degree of evolutionary development. Those of the Greta measures are slightly harder, but other physical and chemical properties are similar. The slight difference in hardness may be due to advanced metamorphism, but it could also be caused by the greater pressures attained in the Greta measures. It is, however, a very small degree of difference, when we consider that the Greta torbanites antedate those of the Upper Coal Measures by a length of time equivalent to half of the Permian period.

During the latter part of the Mesozoic Era and early Tertiary time, the deposits probably remained almost unchanged, and elevation and erosion of Triassic and Kamilaroi sediments, during Tertiary and Pleistocene time, have brought to the surface, once again, the ancient algal deposits which are now hard, compact and chemically-stable torbanite.

Brief Summary of Major Events in the Origin of Torbanite.

The regional environment was that of low-lying marginal areas of Permian coal-measure deposition, receiving large quantities of water and sediment from mountain streams, subjected to frequent rejuvenation and flooding. Local conditions, promoting algal development, were obtained in isolated lakes formed by washing out of silt and peat beds, and by meanders being cut off from main channels which carried water and sediment across the marginal areas of deposition. Water entered the lakes by percolating from flowing streams through peat bogs, marshes, and sand beds. This water carried dissolved and suspended mineral matter with small quantities of humic degradation products. Variations in water-level, in the main channels, alternately filled and emptied the lakes, preventing the establishment of either terrestrial or sub-aerial plant-vegetation. When the lakes were filled in spring or summer, the Permian ancestor of *Botryococcus Braunii*, under suitable climatic conditions, flourished and took possession of the water. After the algal cells had died and decayed, the fatty and cuticular skeletons of algal colonies sank from the surface, or were carried down with sediments to form layers of sapropel on the lake-beds. In some lakes, seasonal growth of algae, during successive years, built up several layers of sapropel, separated by bands of clay or canneloid peat. These bands were due to the settling of sediment, or introduction of vascular-plant sapropel, in the absence of the alga. The deposits were finally covered with silt or peat beds to become part of the coal-measure strata. After burial, polymerization of the algal substance and the weight of overlying beds, changed the deposits to relatively hard, compact material, although, in some cases, siliceous waters attacked the organic matter and partially replaced it with chalcedony. Metamorphism continued during the immense length of time the deposits remained buried, under pressures up to 9,000 lb. per sq. in. and temperatures of 100° to 150°F. The algal remains were subjected to natural carbonization, but its effect was limited, owing to stability brought about by early polymerization. Subsidence of the area of deposition ceased at the close of Triassic time, and transformation to torbanite was completed during the latter part of the Mesozoic Era. Tertiary elevation brought the coal-measures to the surface, resulting in dissection and the exposure of torbanite in existing outcrops.

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EXPLANATION OF PLATE I.

A.—Vertical section of torbanite showing the collapsed central cavities of algal colonies. Baerami deposit. (× 125.)

B.—Horizontal section of torbanite, illustrating the botryoidal appearance typical of compound colonies. Hartley Vale deposit. (× 150.)

C.—Vertical section of torbanite showing oval-shaped structures representing oblique sections of thimbles. Wollar deposit. (× 1,000.)

D.—Horizontal section of torbanite showing funnel-shaped structures representing the basal portions of old thimbles. Hartley Vale deposit. (× 750.)

E.—Vertical section of torbanite showing compound colonies with branching lines formed by the margins of simple colonies. Morts Upper Seam, Katoomba. (× 250.)

F.—Spore in horizontal section of coal. (× 50.)

G.—Spores in vertical section of coal. (× 45.)